Nuclear Engineering and Technology 48 (2016) 360–367

Available online at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Design and Optimization for the Windowless Target of the China Nuclear Waste Transmutation Reactor

Desheng Cheng *, *Weihua Wang, Shijun Yang, Haifei Deng, Rongfei Wang, and Binjun Wang*

Institute Applied Physics of AOA, Huangshan road No 451, Shushan, Hefei, Anhui 230031, China

ARTICLE INFO

Article history:
Received 15 July 2015
Received in revised form
14 October 2015
Accepted 12 November 2015
Available online 17 December 2015

Keywords:
China Nuclear Waste Transmutation Reactor
Lead–Bismuth Eutectic
Simulation
Windowless Target

ABSTRACT

A windowless spallation target can provide a neutron source and maintain neutron chain reaction for a subcritical reactor, and is a key component of China's nuclear waste transmutation of coupling accelerator and subcritical reactor. The main issue of the windowless target design is to form a stable and controllable free surface that can ensure that energy spectrum distribution is acquired for the neutron physical design when the high energy proton beam beats the lead–bismuth eutectic in the spallation target area. In this study, morphology and flow characteristics of the free surface of the windowless target were analyzed through the volume of fluid model using computational fluid dynamics simulation, and the results show that the outlet cross section size of the target is the key to form a stable and controllable free surface, as well as the outlet with an arc transition. The optimization parameter of the target design, in which the radius of outlet cross section is 60 ± 1 mm, is verified to form a stable and controllable free surface and to reduce the formation of air bubbles. This work can function as a reference for carrying out engineering design of windowless target and for verification experiments.

1. Introduction

In the China nuclear waste transmutation reactor (CNWTR), a neutron source will be produced by a high-energy proton beam beating liquid lead–bismuth in the windowless target [1]. The neutron has a nuclear reaction with the nuclear waste (such as Minor-actinide (MA), Long lived fission product (LLFP)) in the subcritical blanket, which can be used to transmute high-level radioactive nuclear waste, and to produce nuclear fuel, generate electricity, etc. The system is mainly composed of the proton beam accelerator, spallation target, subcritical reactor, etc. [2]. The spallation target is the key component for coupling the accelerator with the subcritical reactor. The target material is bombarded by a high-energy proton beam and withstands high temperatures and strong neutron irradiation at the same time. Currently, the lead–bismuth eutectic (LBE) is the first

* *Corresponding author.*
E-mail address: 455611846@qq.com (D. Cheng).
http://dx.doi.org/10.1016/j.net.2015.11.007

choice for the spallation target material and the coolant of the core blanket, because it has good neutronics performance, radiation resistance, and heat transfer performance, low chemical activity in contact with air and water, good safety performance, as well as a low melting point (123 °C) and high boiling point [3].

According to the interface type between the proton beam vacuum and the liquid LBE in the spallation target, the spallation target is mainly categorized into window and windowless targets [4]. Window targets cause serious problems such as short lifetime and the need for cooling due to high-energy proton bombardment, fast neutron irradiation damage induced embrittlement, heat load impact creep, and corrosion of liquid metal flow [5]. Therefore, the liquid metal windowless target is chosen. In the case of windowless target, the proton beam directly hits LBE, which is in contact with the vacuum tube. There will be a free surface between the vacuum and the target material. Compared with the window target, the windowless target enjoys the following advantages: no target window cooling or proton energy attenuation problem; no need to bear the damage caused by the strong high-energy proton or neutron irradiation on the window structure material, and a match between the target unit lifetime and the fuel assembly. However, the instability of the free liquid surface of windowless target may affect neutron distribution and physical and thermal properties of the subcritical reactor [6,7]. Therefore, the formation and control of the free liquid surface is one of the key problems of design and application of the windowless target. The aim of this study is to find out an optimum design scheme of target by assessing stable and controllable free surface performance. A description of the CNWTR system and windowless target are introduced in Sections 2.1 and 2.2. The coupling model of target and core and the boundary conditions are outlined in Section 2.3. In Section 3, the LBE flow characteristics of target are assessed on the condition of the coupling target and core. The design scheme is optimized in Section 4 to form a stable and controllable free surface and to reduce the formation of air bubbles. Section 5 presents the concluding remarks.

2. A description of CNWTR and windowless target

2.1. A description of CNWTR

As shown in Fig. 1, an accelerator driven system (ADS) system is composed of the accelerator system, subcritical reactor, Brayton power systems, nuclear waste reprocessing system, etc. [8,9]. The reactor section is mainly composed of a spallation target system, the reactor vessel and support structure, blanket, refueling system, the circuit system, security system and related auxiliary system, etc. [10]. The external part of the reactor is composed of the secondary circuit system, including Brayton power generation and grid system, nuclear waste reprocessing system, etc.

As shown in Fig. 2, the subcritical reactor adopts pool type reactor structure cooled by LBE. Under normal operation conditions, the support of the reactor structure, blanket, and primary circuit of the heat transport system are submerged in LBE [11]. The integrated reactor is divided into hot and cold areas by the support structure and blanket barrel. The primary circuit system consists of three intermediate heat exchangers and three primary circuit pumps. A high power mechanical pump is located in the lower part of the cool zone of reactor, which drives the low temperature LBE into a flow distribution box at the bottom of the blanket [12]. LBE flows through the distribution box into blanket, which takes the high power density nuclear heat from the fuel assemblies. The high temperature LBE flow is driven by the primary circuit pump and gravity, which takes heat exchange between the interior concentric tube heat exchanger and high pressure helium gas (8 MPa) of the secondary circuit. After heat exchange, the LBE flows into the cold area. Helium gas is employed for the coolant in the secondary circuit, which will flow into the Brayton power system outside the reactor [13]. The main parameters of the reactor are shown in Table 1.

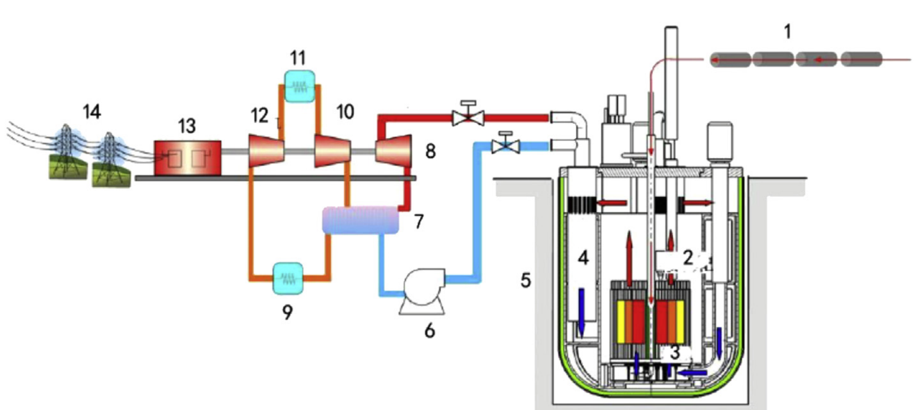

Fig. 1 – Overview scheme of China nuclear waste transmutation reactor. 1, accelerator; 2, spallation target; 3, core; 4, heat exchanger; 5, reactor; 6, helium blower; 7, regeneration; 8, turbine; 9, precooling; 10, high-pressure compressor; 11, intercooling; 12, low pressure compressor; 13, generator; 14, network.

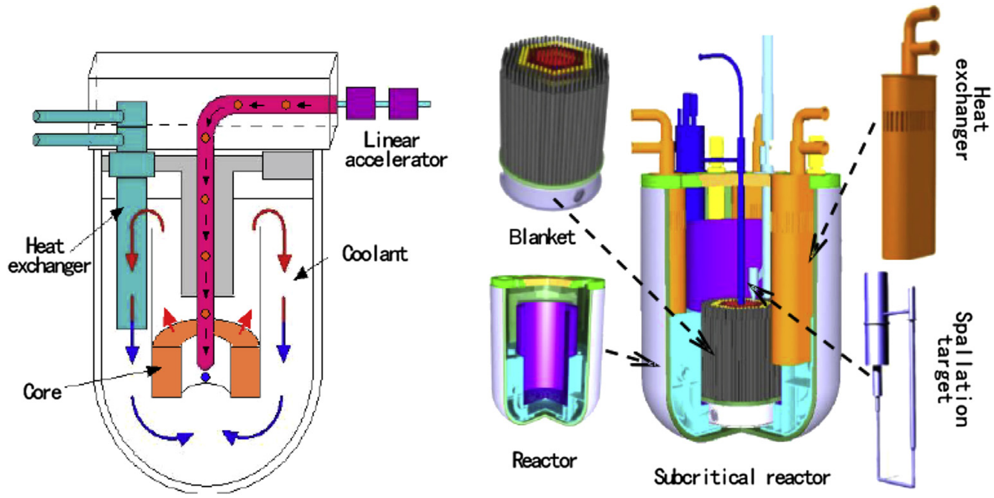

Fig. 2 – China nuclear waste transmutation reactor principle and reactor structure.

2.2. *The design scheme of windowless target*

As shown in Fig. 3, windowless target is a double concentric tube; the interior is the proton beams tube; the exterior channel between layers is for LBE flow; the LBE flows into the spallation target along the guide plate to form a free surface. Above the free surface is the proton beam with the pressure of only 10^{-2} Pa, almost a vacuum. To prevent LBE from moving upward into the proton beam tube and affecting the spallation reaction, there is a need for a stable free surface, therefore, the formation and the control of the free liquid surface is the key issue for the spallation target design, which directly affects the spallation neutron energy distribution and its coupling efficiency with core fuel assembly.

The main design parameters of windowless target are as follows: proton beam energy of 1.5 GeV; beam current of 10 mA, tube diameter of 200 mm; coolant inlet temperature of 230 °C; and velocity of 1.71 m/s. LBE driven by a mechanical and electromagnetic pump forms a closed loop, which takes away the nuclear heat deposition of the target exchanged with the secondary circuit.

Table 1 – Main parameters of China nuclear waste transmutation reactor.

Parameters	Units	Values
Thermal power of reactor	MW	966
Accelerator beam power	MW	15
Proton beam energy	GeV/mA	1.5/10
Import/output temperature of LBE	°C	330/480
Average flow velocity of LBE	m/sec	1.46
Initial K_{eff}	–	0.98
TRU first fuel loading	ton	4.4
MA transmutation rate	kg/yr	365
Average neutron energy	keV	540
Line power density (ave./max.)	w/cm	170/177
Lead bismuth quality inventory	ton	~4,000
Heat exchanger power	MW	320×3
Mass flow rate of heat exchanger	t/sec	14.6

ave., average; K_{eff}, efficiency K; LBE, lead–bismuth eutectic; MA, Minor-actinide; max., maximum; TRU, Transuranics.

2.3. *Model and boundary conditions*

According to the CNWTR design scheme, a simplified 3D model of the spallation target is shown in Fig. 3. Considering the symmetry of the reactor, 1/2 coupling model of target and core is shown in Fig. 3A. The outside target area is the buffer area, and outside buffer area is the fuel area (according to the difference of the burn-up divided into inner, middle and outer fuel area). A gas–liquid two-phase model is selected, and the gas phase is air, as the proton beam tube is virtually a vacuum, with the reference pressure set to 10^{-2} Pa; the pressure reference point is at the top of the proton beam tube. The liquid phase is the LBE, divided into spallation target loop and core circuit. Starting from the concentric channel outside the proton beam tube; LBE flows along the guide plate into the spallation target area, and inlet velocity and temperature are 1.71 m/s and 593 K respectively. The Reynolds number is about 3,672,000. It was reported that the SST turbulence model provides a better performance than the $k-\varepsilon$ and the $k-\omega$ turbulence models on the prediction of the stagnation flow region [14]. The automatic wall treatment allows the application of coarser meshes near walls than typical low Reynolds number treatments. In the present study, therefore, the SST turbulence model with the automatic wall treatment was applied, and the absolute criterion of the residuals is $1e^{-7}$. As a coolant, core circuit LBE flows from the bottom to the top along the fuel assembly, and the inner fuel area is connected with the buffer area. The inlet velocity of inner, middle, and outer fuel area are 1.29 m/s, 1.28 m/s, and 1.15 m/s, respectively, and all the inlet temperature is 603 K. Calculated through the neutron physics, the thermal power density distribution of the spallation target and the core blanket of nuclear fuel areas are given in the literature [3]. Fig. 3B for the spallation target is an axisymmetric grid model; the smallest size of mesh is 0.1 mm; the number of grid cell of the 3D model is 1,295,374; the direction of gravity is vertically downward, the value is 9.8 m/s^2, and the time step is 0.0001s. The number

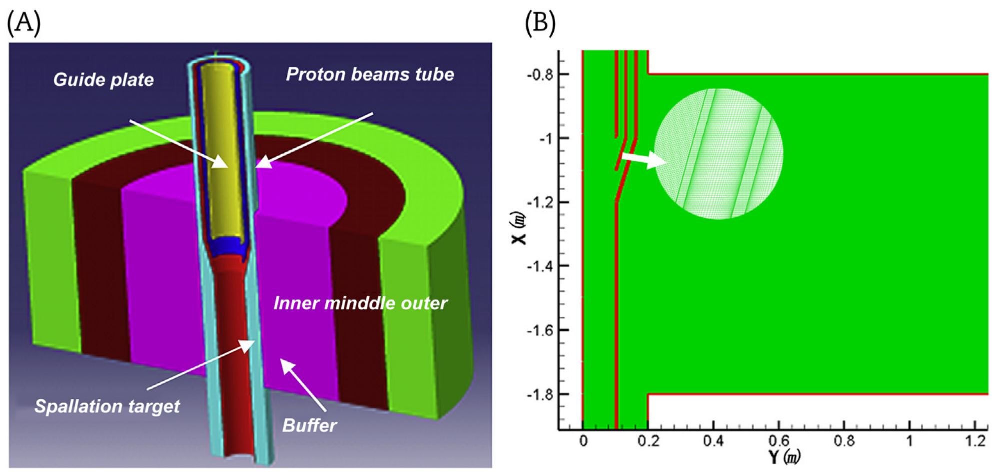

Fig. 3 – Numerical simulation model. (A) Three-dimensional model of coupling target and core; (B) part of axisymmetric grid model.

of the grid cells is double for verification of the mesh independence. There is little difference shown when comparing the calculation results of the two models.

3. Results and discussion

As shown in Fig. 4, there is a two-phase contour distribution for spallation target and core. The blue liquid phase is LBE, the red gas phase is air. The gas is approximately the vacuum. From the diagram of gas–liquid distribution, the LBE does not form a free surface in the spallation target area and LBE flows out from the outlet of spallation target directly. Through the analysis, the conclusion can be drawn that, due to the vertical

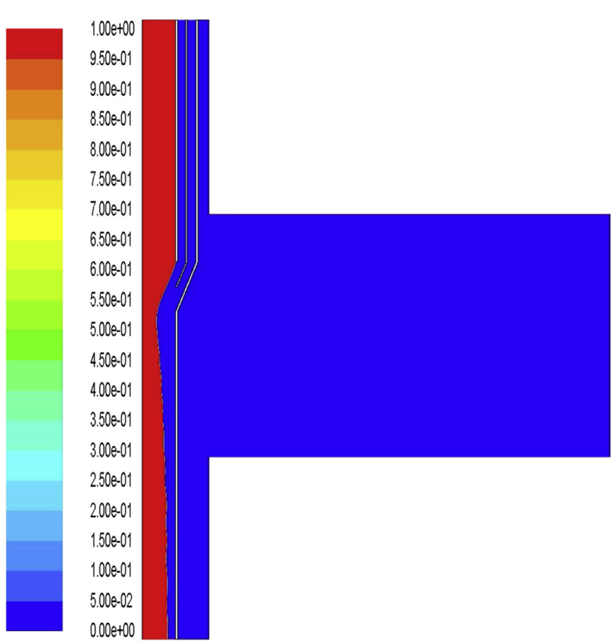

Fig. 4 – Two-phase distribution of coupling target and core.

spallation target, LBE is imported along the guide plate into the spallation target, speeds up under the influence of gravity acceleration, and is allowed to flow out along the spallation target wall directly. It can also be seen that, at constant mass flow rate under certain conditions, the flow section is smaller and smaller along the flow direction.

In Fig. 5, the pressure contour distribution is shown for the original design scheme of coupling the spallation target and core. In Fig. 5A, as the LBE flows from the bottom of the fuel assembly to the top, the pressure drops greatly at the fuel assembly, with the maximum pressure drop of 1.87 bar, but it can be seen from Fig. 5B that the pressure drop between the inlet and the outlet of the spallation target is relatively small at about 1 bar. The pressure drop is mainly formed in the part of the concentric ring tube. In the spallation target area, as a result of the gas phase connecting the proton beam and spallation target area, the pressure is almost equal.

Fig. 6A shows the velocity contours distribution of the original design scheme of the spallation target and core. As shown in the figure, LBE in the fuel area flows comparatively evenly. Inner fuel area and buffer area is communicated with each other, the LBE flowing into the fuel area shunts to the buffer area, and thus the velocity of the LBE flow, decreases at the junction of the inner fuel area and buffer area. The LBE flowing into the buffer area flows out from the top of the junction of the inner fuel area and buffer area. The flow speeds in the corner with the maximum velocity of 5.5 m/s.

Due to the acceleration of gravity, the LBE, flowing along the guide plate into the spallation target, speeds along the wall and the average velocity reaches 5.9 m/s at the outlet. The LBE flow drives the air in the proton beam tube to flow down. As shown in Fig. 6A, the cross section of air flow is relatively small for LBE flowing out of the guide plate, as the cross-sectional of LBE flow dwindles along the LBE flow direction. The cross section of the air flow is large, so the velocity of air flow decreases accordingly, with the maximum velocity of

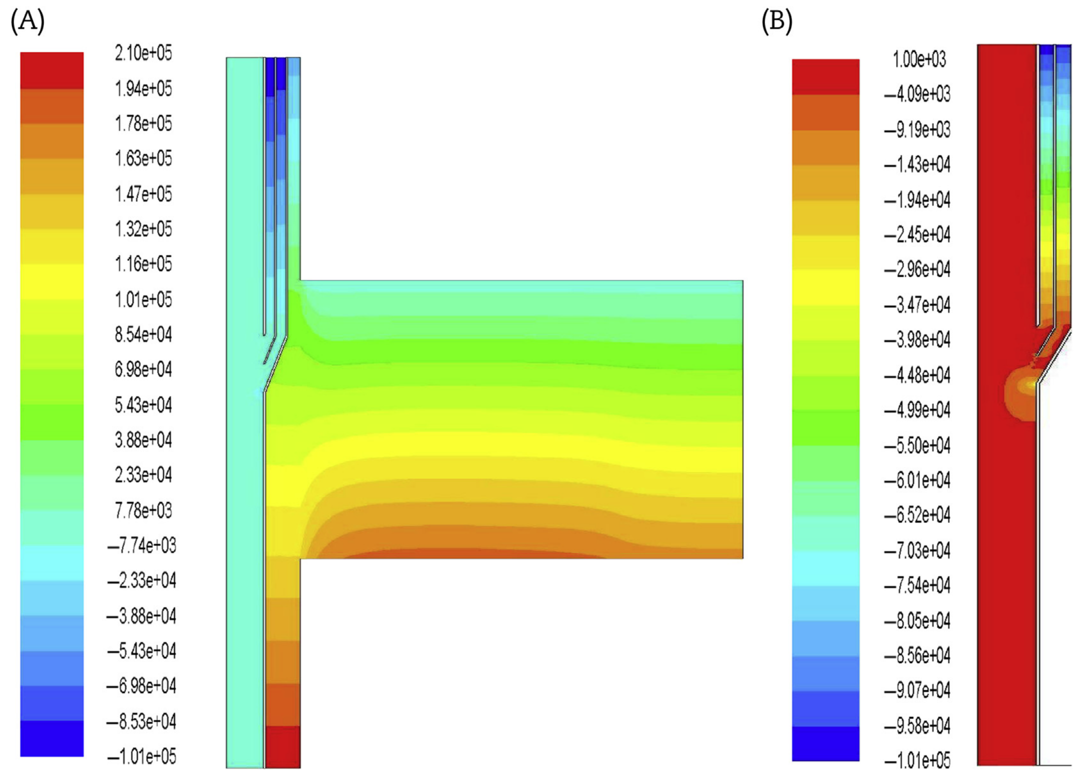

Fig. 5 – Pressure distribution contours of coupling target and core. (A) Coupling target and core; (B) the spallation target.

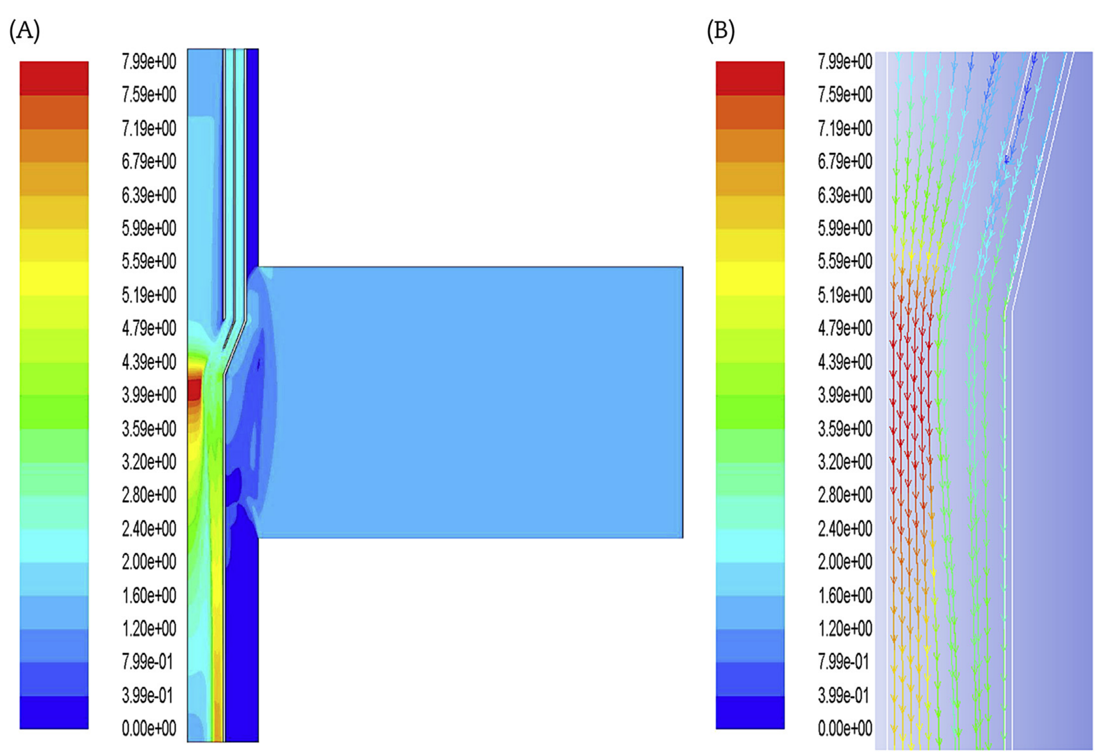

Fig. 6 – LBE velocity distribution of coupling reactor and target. (A) Coupling target and core; (B) the spallation target region. LBE, lead–bismuth eutectic.

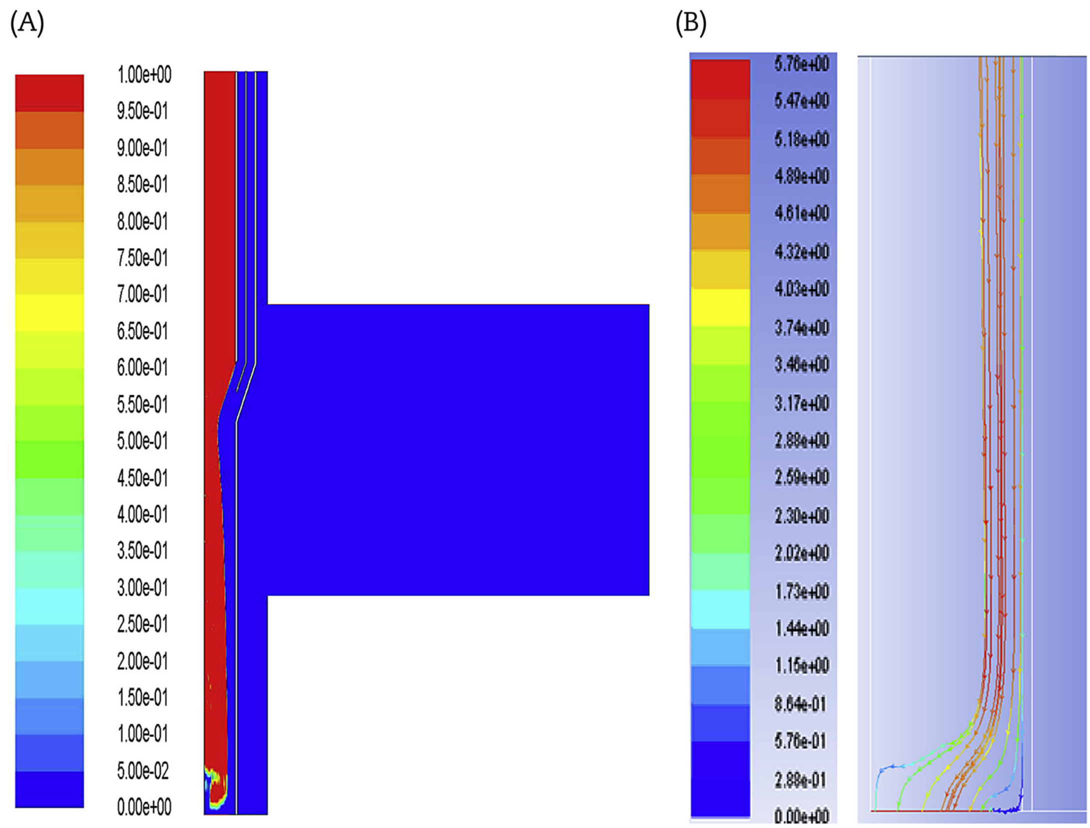

Fig. 7 – The simulation of 4/5 outlet radius model of the original design scheme. (A) Contour of two phase distribution; (B) particle line tracking of lead–bismuth eutectic.

7.99 m/s at the outlet of the guide plate, as the red vector velocity distribution shown in Fig. 6B.

In accordance with the calculation results of coupling target and core, the original design scheme of the spallation target, the LBE flow into the spallation target flows out directly and there is no free surface formed in the spallation target region. In order to form a free surface in the spallation target, the outlet cross section of the spallation target needs to be reduced. Therefore, the original design scheme of the spallation target needs to be adjusted and optimized.

4. Design optimization and conclusion

In order to adjust the outlet cross section radius of the flow to form a free surface in the spallation target, 4/5 outlet radius model of the original design scheme is calculated. As shown in Fig. 7, there are separately the two-phase contour distribution of the spallation target and the particle line tracking of LBE flow.

As clearly shown in Fig. 7, the free surface is still not formed when the outlet radius of the LBE flow reduces to 4/5, so the outlet section radius needs to be further reduced. It can also be seen from Fig. 7 that there is shock wave in the spallation target outlet, mainly because there is no arc transition when the outlet radius of the LBE flow of spallation target is reduced, so the LBE flow dashes against the obstacle and changes the flow direction. As shown in Fig. 7A, there is a collision wave in the outlet of the LBE flow of the spallation target, so a relatively stable free surface cannot be formed. In addition, the outlet section without arc transition leads to increasing flow resistance. Therefore, the arc transition should be adopted to optimize the outlet design parameter of the spallation target.

The outlet model of the spallation target needs an arc transition to reduce the outlet radius gradually. In this study, the calculation model of the outlet of the spallation target is established, as shown in Fig. 8A, with an arc transition. As shown in Fig. 8B, there are 10 kinds of outlet radius available for choice; the interval of the 10 kinds of outlet radius is 10 mm; the radius is shown in Fig. 8B. The 10 models are calculated, and the two-phase distribution contours are shown in Fig. 9.

As can be seen from Fig. 9, in the cases (a–c), the outlet radius is too large to form a free surface in the spallation target; in the cases (d–f), there is a free surface formed in the spallation target, but the height of the free surface is too low to meet the design requirement of the spallation target. When the level of the free surface is lower than the height of the outlet of the guide plate, the LBE flowing out along the guide plate will fall into the free surface freely, making the free surface difficult to keep stable. In addition, when the LBE falls into the free surface, part of the air is taken into the

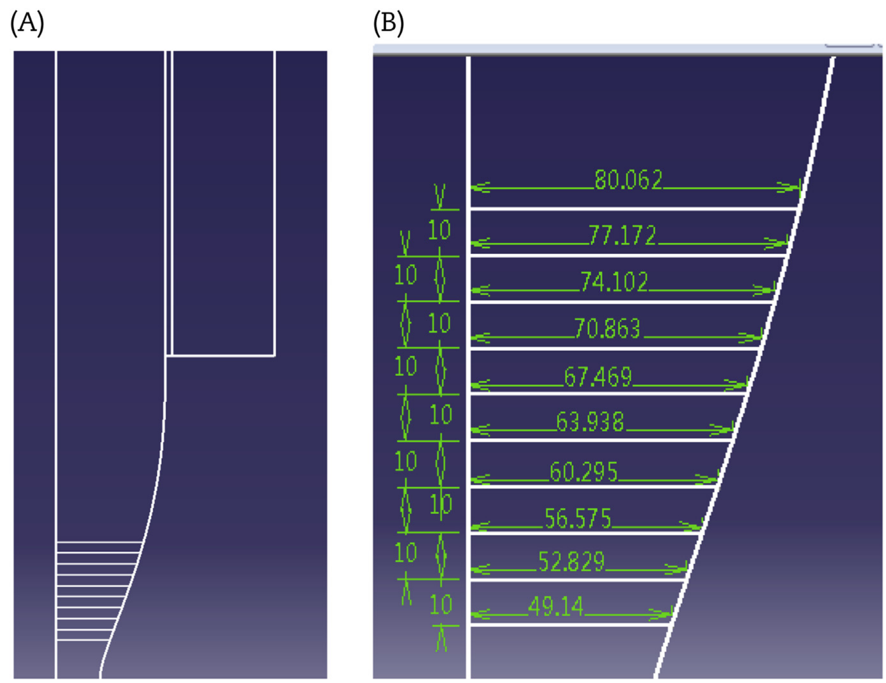

Fig. 8 – Outlet model of the spallation target. (A) Outlet model with arc transition; (B) 10 cases of the outlet radius of the proton beam tube.

LBE. It can be seen clearly from the three calculation results that many air bubbles are generated under the free surface, and this will affect the efficiency of the spallation neutron generation. In the cases (g–i), the height of free surface is higher than the outlet of the guide plate. The formed free surface is relatively stable and there is only a small amount of bubbles generated under the free surface. As the outlet radius reduces, the height of the free surface is higher and

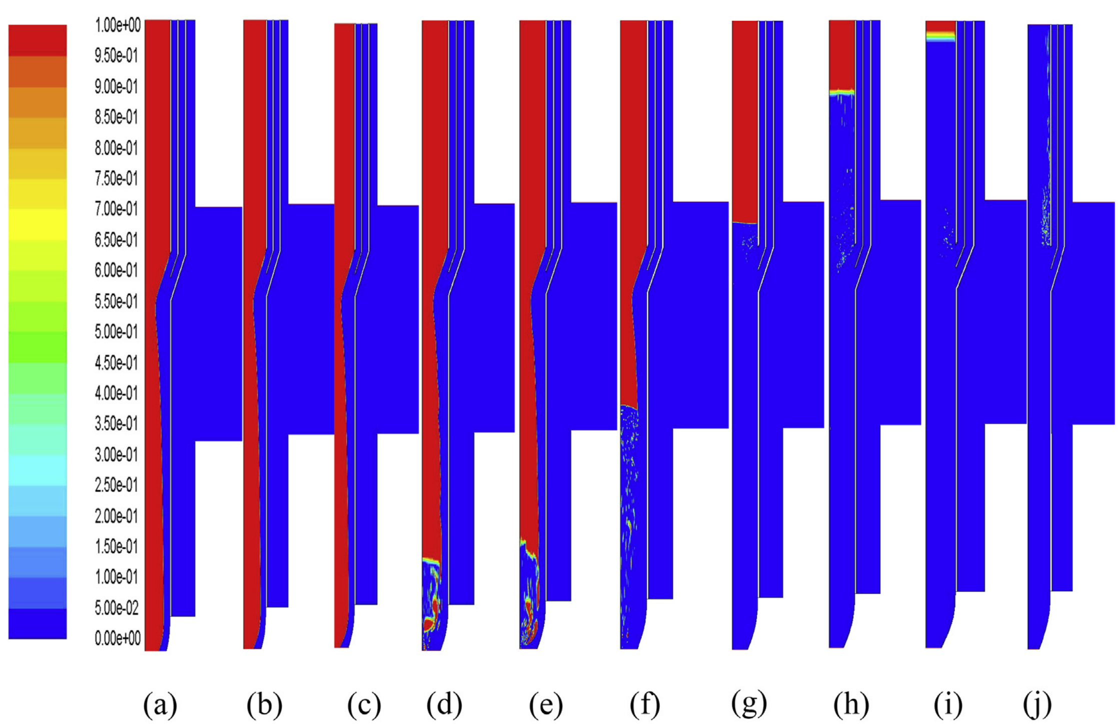

Fig. 9 – Two-phase distribution contours of 10 cases of outlet radius (r). (a) r = 80.1 mm; (b) r = 77.1 mm; (c) r = 74.1 mm; (d) r = 70.8 mm; (e) r = 67.4; mm; (r) r = 63.9 mm; (g) r = 60.3 mm; (h) r = 56.6 mm; (i) r = 52.8 mm; (j) r = 49.1 mm.

higher. In the case (j), the free surface is beyond the inlet of the proton beam tube and the LBE overflows; therefore, case (j) cannot be chosen.

It can be concluded that case (g) can be used as the engineering design verification options from the calculation results of 10 kinds cases of outlet radius, and the scheme can ensure the free surface height meets the demands of neutron physics design, which enables the neutron distribution produced by the high-energy proton beam to beat LBE target bombardment and the energy spectrum to meet the requirements of the core blanket.

The instability of the free surface of windowless target may affect the spallation neutron distribution and the evolvement efficiency of the coupling subcritical reactor. Therefore, the formation and control of the free liquid surface is one of the key issues for the windowless target design. In this study, numerical simulation and optimization verification were carried out for the windowless spallation target, so the conclusions can function as a reference for engineering design and experiments. The main conclusions are as follows:

(1) In windowless target, when the mass flow rate of the inlet is constant, the size of the outlet cross section is the key to forming and controlling the free surface. As the cross section of the outlet is decreasing, the height of the free surface in the spallation target will rise accordingly. When the radius of outlet cross section is adopted in a certain range (such as the g scheme of radius of 60 ± 1 mm), the free surface is a little higher than the outlet of the guide plate. In this case, the free surface is stable and controllable.

(2) The outlet design of the spallation target requires the employment of arc transition, but not a rectangular transition, for the arc transition can help form a stable free surface.

(3) When the height of the free surface is lower than the outlet of the guide plate, the LEB will fall into the free surface, making the free surface unstable. At the same time, there will be a lot of bubbles formed under the free surface, and this will exert a great influence on high-energy spallation neutrons distribution and generation efficiency.

Conflicts of interest

All authors have no conflicts of interest to declare.

Acknowledgments

This work is supported by the Natural Science Foundation of China under grant No.91326101.

REFERENCES

[1] A. Batta, A.G. Class, K. Litfin, Th. Wetzel, V. Moreau, L. Massidda, S. Thomas, D. Lakehal, D. Angeli, G. Losi, K.G. Mooney, K. Van Tichelen, Experimental and numerical investigation of liquid-metal free surface flows in spallation targets, Nucl. Eng. Des. 290 (2015) 107–118.

[2] W.H. Wang, G.M. Liu, S.H. Huang, B. Yang, J.H. Yang, D.L. Chu, H.F. Deng, Numerical Analysis of Two-phase Flow and Heat Transfer of Fuel Particles and Liquid Metal for Waste Transmutation Blanket, 2013, IEEE 25th Symposium on Fusion Engineering (SOFE), San Francisco, California, USA, 2013, pp. 1–5.

[3] C. Rubbia, J.A. Rubio, S. Buono, F. Carminati, N. Fiétier, J. Galvez, C. Gelès, Y. Kadi, R. Klapisch, P. Mandrillon, J.P. Revol, C. Roche, Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier, European Organization for Nuclear Research, Geneva, CERN/AT/95–44(ET), 1995.

[4] Z. Chen, Y. Wu, B.X. Yuan, D.M. Pan, Nuclear waste transmutation performance assessment of an accelerator driven subcritical reactor for waste transmutation (ADS-NWT), Ann. Nucl. Energy 75 (2015) 723–727.

[5] N. Ai, J.Y. Yu, Y.W. Yang, Thermal-hydraulic analysis of PDS-XADS spallation target, At. Energy Sci. Technol. 47 (2013) 260–265.

[6] L. Cinotti, G. Gheradi, The Pb–Bi cooled XADS status of development,, J. Nucl. Mater. 301 (2002) 8–14.

[7] H. Ait Abderrahim, P. d'Hondt, MYRRHA: a European experimental ADS for R&D applications status at mid-2005 and prospective towards implementation, J. Nucl. Sci. Technol. 44 (2007) 491–498.

[8] M. Dierckx, D. Van Dyck, L. Vermeeren, W. Bogaerts, Research towards ultrasonic systems to assist in-vessel manipulations in liquid metal cooled reactors, IEEE Trans. Nucl. Sci. 61 (2014) 2024–2033.

[9] Venneri F. Laur, A Roadmap for Developing Accelerator Transmutation Accelerator Transmutation of Waste (ATW) Technology, A Report to Congress, Department of Energy, Washington DC, USA, 1999.

[10] D. Barni, P. Michelato, D. Sertore, Theoretical and experimental evaluation of the windowless interface for the TRASCO-ADS project, Am. Vacuum Soc. 22 (2009) 1810–1815.

[11] Y. Kurata, T. Takizuka, T. Osugi, H. Takano, The accelerator driven system strategy in Japan, J. Nucl. Mater. 301 (2002) 1–7.

[12] W.S. Park, U. Shin, S.J. Han, T.Y. Song, B.H. Choi, C.K. Park, HYPER (Hybrid Power Extraction Reactor): a system for clean nuclear energy, Nucl. Eng. Des. 199 (2000) 155–165.

[13] C. Chen, J. Zou, J. Zheng, M.P. Sun, H.L. Chen, Development and testing of the code for automatic generating of multi-temperature continuous-energy neutron cross section libraries, Nucl. Sci. Techn. 25 (2014) 050602.

[14] W. Vieser, T. Esch, F. Menter, Heat Transfer Predictions Using Advanced Two Equation Turbulence Models, CFXTech. Memorandum, CFX-VAL10/0602, 2002. Available from: http://www.software.aeat.com/cfx/.